Permeability of sealing walls
La perméabilité des murs de sûreté

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ABSTRACT: The paper deals with problems of the permeability of diaphragm walls made of self-hardening suspensions, reinforced concrete prefabricated or monolithic walls, used for sealing excavation pits, for the protection of the subsoil below flood control dams, for providing weir stability, for the protection of groundwaters from pollution and the solution of numerous other tasks. One of the most important problems is providing long-term efficiency of these structural elements. The development of long-term permeability of sealing walls is influenced by a number of different factors. Information submitted here is based on the experience from several successfully completed engineering projects in the Slovak Republic.

RÉSUMÉ: La présente contribution traite des problèmes de la perméabilité des voiles souterrains en mélanges auto-durcissant (argilo-ciment), préfabriqués en béton armé ou monolitiques. Il s'agit des élements utilisés pour rendre étanche les fouilles, pour protéger les sous-sols des digues, pour assurer la stabilité des barrage, pour protéger les nappes fréatigues de la polution et pour la solution de maintes autres problèmes. Un des problèmes les plus importants est d'assurer leur efficacité a long terme. Le développement de la permeabilité des voiles est influencé par de nombreux facteurs. Les informations apporteés sont issues de plusieurs ouvrages d'art réalisés avec succès sur le territoire de la Républik Slovaque.

1. INTRODUCTION

We have published several papers concerning the problems of sealing excavation pits for the hydropower plant and navigation locks foundation of the river power project Gabčíkovo in the proceedings of international conferences on soil mechanics and foundation engineering. This water scheme on the Danube river has been a successful achievement and was put into operation in 1992 in the territory of Slovakia.

In San Francisco (1985) the paper dealt with the knowledge obtained from the verification section, attention being focused on the development of high-quality sealing elements, meeting the project requirements.

In Nurnberg (1986) we submitted information on the excellent efficiency of sealing elements used in the construction of excavation pits at Gabčikovo, and on the successful completion of the system aimed at the localization of more permeable locations. Even in spite of their existence it was not necessary to perform any additional sealing. From the pits, for the hydropower plant and for navigation locks water discharge, to 0,3 m^3/s had been pumped, representing a substantially lower amount than assumed in the project (2,0 m^3/s).

In Rio de Janeiro (1989) emphasis was placed on issues involving the transfer of substances, released from sealing elements, caused by groundwater, with regard to the potential pollution of close high-quality drinking water resources.

It was not necessary to provide long-term efficiency of the sealing elements in the case of the excavation pits for the river power project Gabčikovo.

Subsoil of the Danube channel damming and waterways in Čunovo, as well as flood control dams in Slovakia between Palkovičovo and Čičov, are protected by means of sealing diaphragm walls, since it was not possible to bond them into impermeable ground. During the catastrophic flood in 1965 the flood protection dam at Čičov bursted causing great damage. In similar cases the long-term reliable efficiency of sealing elements is very important.

Long-term sealing efficiency is to be provided also in cases of excavation pits of underground parts of administrative, transport and other structures. Usually they are built as monolithic or prefabricated diaphragm walls or as pile walls. Several similar structures have been built, or are under construction in the capital of Bratislava.

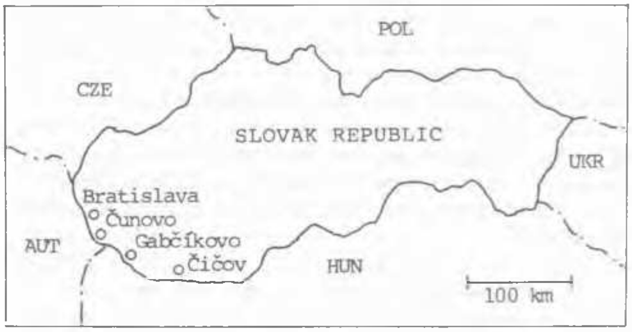

Figure 1. Schematic map of the Slovak Republic with the marked positions of studied localities.

With regard to groundwater protection close to waste disposal sites using sealing walls, experimental results published by Pavilonsky (1985) resulted in fears for their long-term efficiency.

The layout of all the localities mentioned in this contribution are presented in Fig. 1 on the schematic map of the Slovak Republic.

2. SEALING WALLS OF EXCAVATION PITS

At Gabčikovo, where gravelly soils reach down to a depth of more than 300 m, the sealing walls made of self-hardening suspension were bonded into the subsequently grouted bottom. It turned out that the grouting mixtures were extruded along the walls up to the surface which decreased their permeability. The dewatering system within the pits was supplemented by observation wells, for monitoring changes in groundwater levels and flow rates. Thus, it was possible to differentiate water amounts, infiltrating through sealing walls into the pits, and water amounts infil-

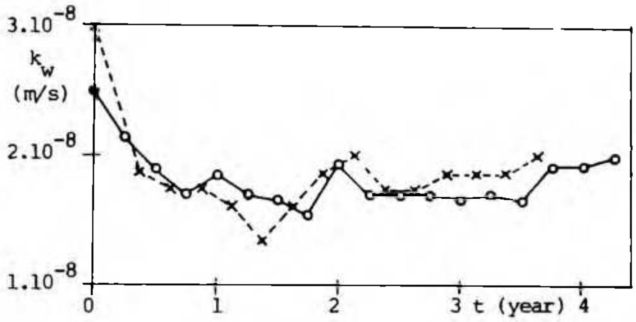

Figure 2. Time development of permeability for sealing walls of self-hardening suspension in Gabčikovo: k_w = permeability coefficient, t = time, o = powerplant, x = navigation locks.

trating through the grouted bottom, and pumped out together from drilled wells.

The permeability coefficient of the walls was computed by means of the relationship

$$k_w = \frac{2Q_w t_w}{(H^2 - h^2)L} \qquad (1)$$

where Q_w = water discharge infiltrating through sealing walls, t_w = wall thickness, H = water depth on the external side of the wall, h = water depth within the pit, L = wall length along the pit perimeter.

The change of the wall permeability in time is presented in Fig. 2. Between values obtained for the hydropower plant and for the navigation locks no higher differences were found. Initial higher values may have been influenced, to a certain extent, by unsteady flow conditions at water level stabilization below the bottoms of excavation pits. After three and a half years elapsed, the wall permeability started to increase negligibly. This could have been caused by inaccurate measurements, or by altering wall permeability. However, the beginning of other processes, which after a longer period could be more significant, cannot be eliminated.

The pit for the construction of the General Credit Bank in Bratislava was safeguarded in the upper part with nails, and in the lower part by means of reinforced concrete prefab elements embeded into self-hardening suspension. Prefabricated elements were anchored at one level, and below the cranes in two rows (Fig. 3). The groundwater level was approximately at the level of the first row of anchor heads. The total depth of the pit being about 12 m, the diaphragm wall was bonded into neogene clays. The building has three underground floors and 24 overhead floors, and is constructed on a foundation plate.

The upper clayey neogene layer, with thin silty or sandy lenses, 10 - 12 m thick, rests upon more permeable silty fine sands, interrupted by clay layers of minor thickness.

To decrease bottom heave during excavation a number of relief wells were drilled, up to 40 m deep. The pumped discharge of about 0,012 m^3/s lowered the average water level by 7 m. This measure turned out to be efficient, since 0,06 m instead of the computed pit bottom was heaved by only 0,04 m. However, water pumping from neogene sands made it rather complicated to differentiate more accurately the portion of water inflow through the diaphragm walls. This discharge was approximately Q_w = 0,001 m^3/s. According to the relationship (1) the average value of the permeability coefficient of prefab reinforced concrete plates in self-hardening suspension has been computed as $k_w = 3.10^{-8}$ m/s.

The prefabricated wall for the foundation of the navigation lock at Čunovo also had similar parameters. Though, it was necessary to leave, under the prefabricated elements, the self-hardening suspension for the connection of the wall to the grouted pit bottom. At one section the wall inclined slightly, in a longitudinal direction, thus causing an opening of a fissure at its surface. In spite of the fact that no more serious problems occurred, the causes of the failure were carefully studied. It was revealed that a part of the wall squeezed, by its weight, into the self-hardening suspension which was not adequately hard. Decreased strength resulted from the dilution of the suspension by local intense groundwater streaming through an extremely permeable gravelly layer.

Figure 3. Excavation pit for General Credit Bank in Bratislava, safeguarded in the upper part with nails, in the lower part with prefabricated reinforced concrete walls.

In the centre of Bratislava, close to the Danube, in conditions straightened by surrounding structures, construction of underground garages with 3-4 floors was started. The foundation pit is safeguarded with monolithic reinforced concrete diaphragm walls with tight joints between neighbouring lamellas, bonded into neogene clays. The permeability of the walls was verified during the period of flood discharge culmination in the Danube. From the 21st to the 24th of October 1996 the water level in the foundation pit in gravelly soils increased only by 0,03 m (without pumping), representing in the given conditions a discharge of Q_w = 0,0001 m^3/s and the wall permeability coefficient of $k_w = 6.10^{-7}$ m/s. Such an excellent quality of walls makes it possible to solve the problem of uplift and stability of the structure even in periods of extremely high floods in the adjacent Danube river by means of pumping only negligible amounts of water from the inner garage space, from the space below the foundation plate.

3 SEALING WALLS UNDER DAMS

Damming up of the Danube bed in October 1992 at Čunovo constituted conditions for putting the hydropower project Gabčikovo into operation. On the site where the damming was performed a relatively vast territory arose, making it possible to construct structures for sporting activities and recreation. However, there also exist other structures - weirs, the navigation lock, the hydropower plant under construction and almost completed - which ensure the operation of the hydropower project. In this area the thickness of sandy gravels reaches more than 100 m, the stability of structures had to be ensured by means of hydraulically imperfect sealing walls. The walls are only 35 m deep, but their long-term sealing efficiency is very important.

In order to control hydrodynamic processes and the efficiency of these sealing walls, at critical points, observation wells for monitoring the water levels, vertical flow and seepage velocities were installed.

Fig. 4 presents one of the profiles for inspection of the sealing efficiency during the Danube damming with the results of measurement.

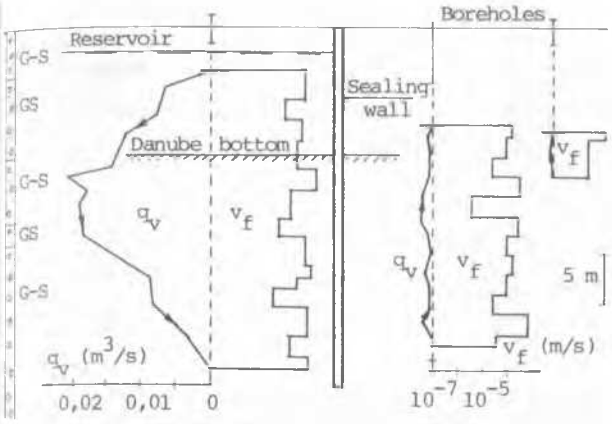

Figure 4. Inspection profile for the sealing wall at the Danube river damming at Čunovo: q_v = vertical discharge, v_f = filtration velocity

Observation wells connect various pressure horizons, thus as a consequence, within the well vertical flow occurs. It can be measured with flow-meters or using tracers. If in the flow direction the vertical discharge (q_v) increases, water flows into the borehole from the surrounding soil. If it decreases, water flows out into the surrounding soil. Analysing the flow field around and in the borehole, it is possible to compute from the vertical discharges in the borehole the filtration velocities in the soil at different depths

$$v_f = \frac{\Delta q_v}{\alpha d \Delta h} \tag{2}$$

(Δq_v = increase or decrease of the vertical discharge in the well section Δh, d = internal diameter of the perforated tube, α = drainage effect of the borehole).

High values of vertical discharges and filtration rates in the borehole are evident in Fig. 4 on the upstream face of the wall. On the downstream face of the wall the flowing is less intense. Water levels on the downstream side, or eventually hydraulic gradients are also used for the elimination of the water level influence in the original Danube bed. There, water levels vary according to the operating mode of the weir gates. Development of the sealing walls efficiency may be estimated according to the development of water levels and velocities of seepage waters.

The hydropower system Gabčíkovo - Nagymaros has not been completed according to the original project. As a consequence our territory downstream of Gabčíkovo is not protected against floods. There, the outflow canal of the project empties into the original Danube bed. In this section, the dikes burst at two places during the flood in 1965 (water discharge in the Danube 6000 m^3/s lasted over 40 days). These failures were caused during an unusually long-lasting flood period, when first the relatively impermeable clayey-silty cover layer was locally destroyed by uplift and then due to the rapid erosion of the subsoil, the dike was also disturbed.

The present conception of protection respects this experience, proceeding from similar hydrologic conditions as in 1965. Hydraulically imperfect diaphragm sealing walls made of self-hardening suspension 20 m deep have been constructed on the upstream face of the dike (gravelly soils are about 100 m deep). The upstream slope of the dam was covered with plastic foil and a protecting fill up to the dam crest.

The pressure line and the velocity field of the water movement below the dam and sealing were verified for isotropic and anisotropic gravelly subsoil by FEM computations. Changes of the sealing efficiency may be estimated on the basis of registrated water levels and seepage velocities.

In Fig. 5 computation results are presented for one of the profiles at Čičov (where the dam bursted in 1965). Without the sealing wall the territory on the downstream side of the dam is instable as well as the dam itself (a). The sealing wall warrants stability over flood conditions lasting 10 days even in isotropic gravel soils (d). The same results were obtained in the case of a flood lasting 40 days and anisotropic gravel soils (c). However, the pressure line reaches above the territory surface when the gravels close to the sealing wall are isotropic (b). In areas, without an impervious cover, liquefaction of sands could occur. Therefore it was recommended to construct an artificial compacted silty layer here.

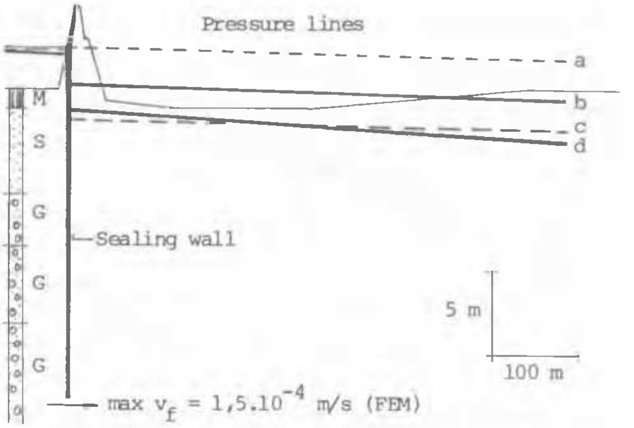

Figure 5. Efficiency of the sealing wall for the protection of dam subsoil at Čičov: a = pressure line for unprotected dam subsoil without a sealing wall, b = pressure line for isotropic subsoil with a sealing wall (T = 40 days, λ = 1), c = pressure line for anisotropic subsoil with sealing wall (T = 40 days, λ = 10), d = pressure line for isotropic medium with sealing wall (T = 10 days, λ = 1), T = duration of flood, λ k_h, k_v = anisotropy, v_f = filtration velocity.

The geological conditions along the Danube are rather complex. It is practically impossible to define precisely the boundaries of individual layers. The assumption of isotropic gravels is not realistic. It was introduced only in order to get a view of the entire range, including the most unfavourable theoretical values.

An additional problem is the stability of sand particles in the pores of gravel soils which due to intense hydrodynamic loading can move. If there are loose spaces where they may be transported (e.g. piping or surface cover broken due to uplift), the dam stability is endangered again. Sealing walls proved to be efficient here, flow velocities in their surrounding decrease, and maximum velocities are shifted below the lower wall end. At maximum velocities the sand particles in the pores of the gravel are stable, then also the dam stability is higher. This can be verified by means of critical velocities.

In our conditions critical velocities computed according to the simple relationships of Sichardt, Ťavoda (1985), Bush and Luckner (1973) are applied for this purpose. The basic characteristic is, first of all, the permeability coefficient of gravel soils. If seepage velocities attain critical values, the sand particles in the pores of the gravel begin to move.

Critical velocities obtained according to the mentioned authors for gravels from the Čičov area are presented in Fig. 6. The maximum filtration velocity below the lower end of the sealing wall, determined by FEM, is marked here by the asterix. It is evident that the stability of sand particles in the pores of the gravel is not jeopardized.

4. SEALING WALLS IN A CONTAMINATED MEDIUM

It is possible to completely seal off, by means of sealing walls, the contaminated space under waste disposal sites and their surroundings. However, they can also be used for increasing the intensity of dispersion processes in the case of groundwater protection from the single accidental spillage of pollution.

Simplified prognosis of pollutants transport by means of groundwater is based on the relationship

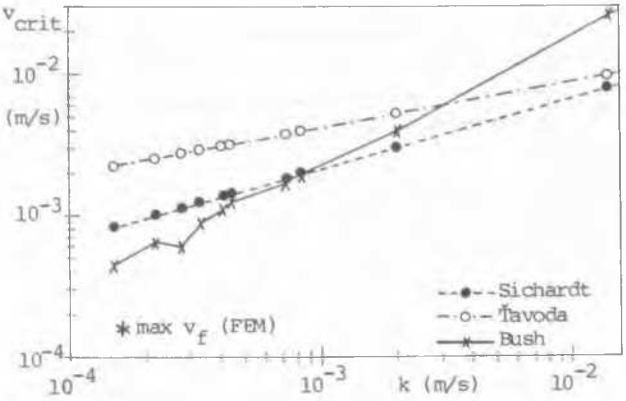

Figure 6. Relationships among critical velocities (v_{crit}) and permeability coefficients of gravel soils (k) in the Cičov area

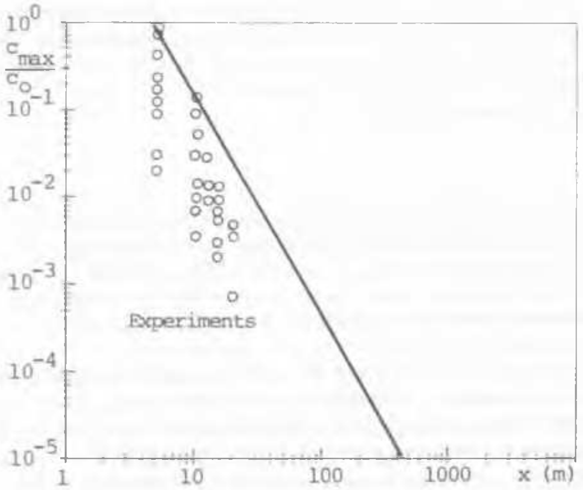

Figure 7. Orientation prognosis of pollutants transport in gravel soils and results of field experiments in Slovakia: c_o = initial pollutants concentration, c_{max} = maximum concentration in the distance x

$$\frac{c_{\max}}{c_o} = \frac{V_o}{2\,A\,n_{ef}\,\sqrt{2\,\pi\,\alpha_L\,x}} \tag{3}$$

where c_{max} = maximum concentration of pollutants in the distance x, c_o = initial pollutants concentration at the intrusion into the medium, having volume V_o, A = area perpendicular to the transfer direction, n_{ef} = effective porosity, α_L = longitudinal dispersivity.

Results of field experiments carried out in gravel soils in Slovakia are presented in Fig. 7 together with the relationship, derived by means of published information on pollutants transfer under similar conditions, by means of the relationship (3) for single leakage having a volume V_o = 10 m^3. If, for instance, a sealing wall were constructed in front of the water resource, which potentially could be endangered by the accidental spillage of pollution, the sealing wall providing an extension of the travel of transfer by 200 m, the maximum pollutants concentration would be decreased by 10000 times.

Results of Pavilonsky's experimental works (1985) are significant for the long-term efficiency of sealing walls. In the case of industrial wastewaters flow, having alkaline and acid reaction, through thin clayey layers with prevailing components of bentonite and kaolinite, the samples show 10- to 1000 times more permeability when compared with clean water discharge. This information cannot be underestimated and due attention should be given to the permeability development of sealing walls in time.

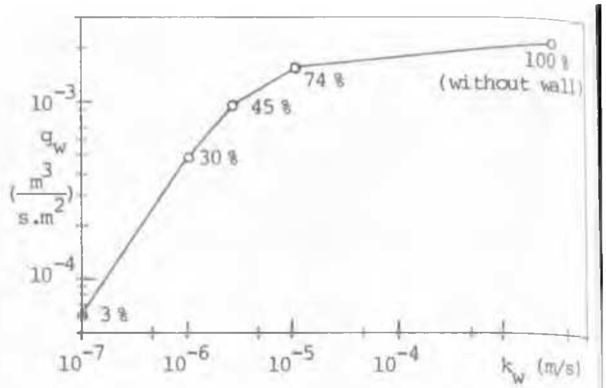

Figure 8. Effect of increasing permeability of by-passed sealing wall on penetrating discharge: q_v = specific discharge infiltrating through the wall, k_w = permeability coefficient of the wall, k = 0,003 m/s = permeability coefficient of soil

In Fig. 8 the results of simple computations are presented, making it possible to obtain an idea of the changes of the seeping discharge in gravel (k = 0,003 m/s) for increasing sealing wall permeability, the sealing wall being by-passed with contaminated water. Wall permeability increased 100 times resulting in more than a 70 % increase of the discharge penetrating the wall.

5. CONCLUSIONS

Slovak joint-stock companies Váhostav Žilina and Hydrostav Bratislava accomplished the construction of high-quality diaphragm sealing walls. Their permeability coefficients are in the range from 6.10^{-9} m/s to 3.10^{-8} m/s. They were mostly used for the sealing of foundation pits, where long-term efficiency was not required. Information on the negative effects of pollutants and other processes make it necessary to place an emphasis on the time dependent permeability of sealing walls: the stability of engineering structures and the groundwater quality require the long-term efficiency of sealing elements.

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